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Surface soil hydraulic properties in four soil series under different land uses and their temporal changes

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Abstract

The concepts of "genoform" and "phenoform" distinguish the genetically-defined soil series and the variation of soil properties resulted from different land uses and management practices. With the repeated field measurements over time, we attempted to understand the difference of soil hydraulic properties among different land uses for a given soil series, and their temporal dynamics. Four soil series (Glenelg, Hagerstown, Joanna, and Morrison) in Pennsylvania with contrasting textures, structures, and parent materials were investigated. Within each soil series, four common land uses (woodland, cropland, pasture, and urban) were examined. At each site of soil series–land use combination, field-saturated and near-saturated hydraulic conductivities, $K(\psi)$, were measured at the soil surface using standard tension infiltrometers at water supply potentials (ψ) of −0.12, −.06, −0.03, −0.02, −0.01, and 0 m. Surface infiltration measurements were repeated at each site in May and October from 2004 to 2006. The analysis of variance indicated that the measurement time (May or October) had the greatest impact on all measured hydraulic conductivities ($p<0.001$), followed by the land use ($p<0.05$ for $K_{\psi=0}$ and $K_{\psi=-0.06}$) and soil series ($p<0.06$ for $K_{\psi=-0.01}$ to $K_{\psi=-0.03}$). The interactions between the time and land use and between the soil series and land use were statistically significant for $K_{\psi=0}$ and $K_{\psi=-0.01}$. When separated by the measurement time, land use showed greater impacts in October than in May, while soil series had greater impacts in May than in October. Among the four land uses, woodland showed less obvious temporal change compared to the other three land uses because of less human-induced impacts and more consistent ground cover. Other three land uses generally showed a higher hydraulic conductivity in May than in October due to the drier initial soil moisture condition and related management practices in the spring that gave rise to more significant macropore flow. The results suggested that the initial soil moisture is an important variable that drives the temporal variation of the surface soil hydraulic properties.

Keywords: Land use; Genoform; Phenoforms; Hydraulic conductivity; Tension infiltrometer

1. Introduction

Soil hydraulic properties, including soil hydraulic conductivity function and water retention characteristics, are affected by soil texture, bulk density, soil structure, and organic carbon content, many of which are strongly influenced by land use and management even though the soil classification may be the same. The concepts of "genoform" and "phenoform" proposed by Droogers and Bouma (1997) distinguish the genetically-defined soil series (i.e., genoforms) and the variation of soil characteristics resulting from different land uses and management practices (i.e., phenoform). Genoforms commonly refer to the soil series with little impact from human activities, e.g., forest soil series, while phenoforms are the soils within the same soil series but have been subjected to considerable changes due to different land uses, e.g., cropland, pasture, and urban. Hence, soil properties at surface and near-surface are considered "use-dependent," while soil properties at the subsurface are relatively use-invariant (Grossman et al., 2001; Lin et al., 2005). While the studies using the concepts of "genoform" and "phenoform" have demonstrated the potentials of improving the efficacy of soil series and land uses as carriers of soil properties, such work has been done mostly in the Netherlands (e.g., Bouma and Droogers, 1999; Pulleman et al., 2000; Sonneveld et al., 2002).

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Additional investigations in other parts of the world using such concepts would be beneficial to enhance the understanding of land use impacts on soil properties and how best to transfer basic soil survey information to hydraulic parameters needed in simulation models. Furthermore, in applying the concepts of genoform and phenoforms, the interactions between the land use and time domain would need to be considered even though the land use remains unchanged over certain period of time.

It is well recognized that soil hydraulic conductivity is a highly dynamic soil property (Lin et al., 2005). The temporal change of land use and management, or natural disturbances and cycles such as diurnal and seasonal changes, can affect soil hydraulic properties. Soil compaction caused by wheel traffic or animal grazing can destroy large pores and therefore reduce saturated or near-saturated hydraulic conductivity (Heddadj and Gascuel-Odoux, 1999; Drewry and Paton, 2005). Tillage can create more large pores for surface soil but may also disrupt pore network connectivity especially for subsurface flow (Bouma, 1991; Buczko et al., 2006). The wetting and drying cycle associated with season change also leads to the temporal variation of soil hydraulic conductivity (Heddadj and Gascuel-Odoux, 1999; Lin et al., 1998). Other factors, such as soil organism activity, root dynamics, and formation of cracks at the surface during dry periods, all contribute to the dynamic nature of soil hydraulic properties in different soils (Messing and Jarvis, 1993; Lin et al., 1998; Rasse et al., 2000).

Soil hydraulic conductivity can be determined by various methods. As a standard tool for *in situ* measurement of field-saturated and near-saturated soil hydraulic properties, tension infiltrometer is able to assess the contribution from soil pores of various sizes to total water flow by controlling the effective pores transmitting the water during the infiltration process (Watson and Luxmoore, 1986; Perroux and White, 1988; Reynolds and Elrick, 1991). Tension infiltrometers therefore have been applied to evaluate soil hydraulic properties, especially those related to macropores and soil structures as influenced by manure application (Miller et al., 2002), tillage practices (Sauer et al., 1990), land use change (Bodhinayake and Si, 2004), vegetation cover difference (Holden et al., 2001), and climatic impacts (Lin et al., 1998; Gupta et al., 2006).

The objective of this study was to investigate the temporal dynamics of surface soil hydraulic properties in four soil series under four different land uses through repeated field measurements using tension infiltrometers. With the repeated measurements over time, we attempted to understand the difference in soil hydraulic properties among different land uses for a given soil series, and to answer the question of whether such difference is a function of time. This investigation should shed light on the temporal nature of genoform and phenoform that has not yet been adequately addressed in the literature.

2. Materials and methods

2.1. Study sites

Four soil series with different soil textures and structures were selected for this study: Glenelg, Hagerstown, Joanna, and Morrison. Glenelg and Joanna series (both *Typic Hapludults*) are located in Chester and Berks County, PA, respectively, representing the Northern Piedmont Major Land Resources Area (MLRA) 148 of the U.S. The other two series, Hagerstown (*Typic Hapludalf*) and Morrison (*Ultic Hapludalf*), are located in Centre County, PA, representing the Northern Appalachian Ridges and Valleys MLRA 147 of the U.S. The sandstone-derived Joanna and Morrison soils had higher sand content but lower silt and clay contents than the limestone-derived Hagerstown and the schist-derived Glenelg soils (Table 1). The overall averaged bulk density was 1.38, 1.47, 1.64, and 1.64 g/cm^3 for the surface soils of the Hagerstown, Glenelg, Joanna, and Morrison soil series, respectively.

Within each soil series, four land uses (woodland, cropland, pasture, and urban) were selected to investigate the impact of land use on soil hydraulic characteristics. Woodland sites represented the land use with relatively small anthropogenic influence. Cropland sites selected had two years of corn and one year of alfalfa, as the typical crop rotation for Pennsylvania agriculture with conventional tillage. Pasture sites were designated as areas that were grazed by animals (cows and horses in this study). Urban sites were selected as recently established residential areas for more than 5 years. All the urban sites have been reseeded with grass that has emerged throughout the area.

2.2. Tension infiltrometer measurements

Five tension infiltrometers were used simultaneously for *in situ* infiltration measurements at each of the 16 sites of the soil series–land use combinations. Tension infiltrometers used in this study followed the design of Ankeny (1992) and commercially-available models (Soil Measurement Systems, Tucson, AZ) with a circular base of 0.232-m in diameter. An Omega PX26-005 DV differential pressure transducer (Omega Engineering, Stanford, CT) and a Campbell CR10X datalogger (Campbell Scientific, Inc., Logan, UT) were used to automatically record the water height change inside the water reservoir every 30 s for all five infiltrometers simultaneously. Another Omega differential pressure transducer was installed on the infiltration disc to monitor the actual potential between the infiltration disc and the contacted soil surface (Walker et al., 2006). This allows for real-time adjustments to achieve the desirable water supply potential when needed.

Site preparation followed the procedures of Lin et al. (1997). Grass or vegetation at each site was carefully trimmed using scissors prior to each infiltration measurement. To minimize near-surface lateral flow, a thin metal ring was inserted into the soil to 1-cm depth. A thin layer of moist fine sand was then applied to smooth local surface variations and to provide a good contact between the base of infiltration disc and the contacted soil surface. Four infiltrometers were placed approximately 1-m apart from each other in a square pattern and a fifth infiltrometer was placed at the center of the square to provide replicates of infiltration measurements at each site. Starting with the lowest potential, six potentials (−0.12, −0.06, −0.03, −0.02, −0.01, and 0 m of water) were applied sequentially to measure apparent

Table 1
Surface soil texture, total carbon content, bulk density (BD), and plant available water (PAW, defined as the difference of volumetric soil water contents at 33 kPa and 1500 kPa) at the 16 study sites

Soil series	Land use	Soil particle size distribution (%)			Total C	BD	PAW
		Sand	Silt	Clay	(%)	(g/cm^3)	(%)
Glenelg	Woodland	24.5	53.4	22.1	11.0	1.13	20.4
	Cropland	26.8	53.5	19.7	1.5	1.50	13.8
	Pasture	46.6	35.9	17.6	3.0	1.58	12.5
	Urban	22.8	58.4	18.8	1.4	1.69	13.7
	Average	30.2 (11.1) ab	50.2 (9.9) bc	19.6 (1.9) b	4.2 (4.5) a	1.47 (0.24) a	15.1 (3.6) b
Hagerstown	Woodland	17.1	63.5	19.4	7.1	0.88	6.3
	Cropland	12.0	67.1	20.9	1.4	1.56	8.7
	Pasture	12.4	63.9	23.7	2.0	1.47	12.8
	Urban	36.3	46.6	17.1	1.2	1.59	8.1
	Average	19.5 (11.5) a	60.2 (9.3) c	20.3 (2.8) b	2.9 (2.8) a	1.38 (0.33) a	9.0 (2.7) ab
Joanna	Woodland	43.4	42.3	14.3	11.00	1.64	7.2
	Cropland	41.9	42.1	16	1.3	1.60	15.3
	Pasture	25.7	57.0	17.3	2.1	1.55	16.7
	Urban	67.8	23.0	9.2	0.5	1.78	4.8
	Average	44.7 (17.4) b	41.1 (13.9) b	14.2 (3.6) a	3.7 (4.9) a	1.64 (0.10) a	11.0 (5.9) b
Morrison	Woodland	89.4	7.5	3.1	12.1	1.40	1.8
	Cropland	63.1	26.7	10.2	0.9	1.85	6.9
	Pasture	73.1	17.6	9.3	1.6	1.64	4.1
	Urban	51.0	31.7	17.3	1.5	1.68	5.8
	Average	69.2 (16.2) c	20.8 (10.7) a	10.0 (5.8) a	4.9 (6.3) a	1.64 (0.19) a	4.7 (2.2) a

In the rows of averages, the number in parenthesis is one standard deviation. The lower letters after the parenthesis indicate the significance test of mean difference among the four soil series at $p<0.1$.

steady-state infiltration rates, Q_ψ ($m^3\ s^{-1}$), under each of these supply potentials (ψ). We used 30 min for −0.12 and −0.06-m potentials, and 15 min for −0.03, −0.02, −0.01 and 0-m potentials based on our experience and field tests. The results showed that apparent steady-state was achieved within the above infiltration time in our study sites. Initial volumetric soil moisture content of each study site was measured *in situ* before running each infiltration test using a Theta probe with a HH2 readout (Delta-T Devices, England). Three readings were taken around the outside of the metal ring for each tension infiltrometer site and then averaged to obtain the mean initial soil moisture content at each site.

Infiltration tests were conducted at the exact same sites in May and October from 2004 to 2006, including a total of four measurements in May 2004, October 2004, October 2005, and May 2006. In order to return to the exact same surface locations, an orange stake was placed near each site. A compass bearing and length was taken at each site to enable getting back to the same location for later measurements. After obtaining apparent steady-state infiltration rates at each of the supplied water potentials, unsaturated hydraulic conductivity (K_ψ) at different potentials and field-saturated hydraulic conductivity (K_{fs}) were calculated using the method described by Reynolds and Elrick (1991). In a piecewise fit, a soil texture/structure parameter, $\alpha_{i,i+1}$ (m^{-1}), over two supply potentials, ψ_i and ψ_{i+1}, can be determined as (Wooding, 1968; Reynolds and Elrick, 1991)

$$\alpha_{i,i+1} = \frac{\ln(Q_{\psi i}/Q_{\psi i+1})}{\psi_i - \psi_{i+1}} \quad (1)$$

The value of α measures the relative importance of the gravity and capillarity forces during water infiltration in unsaturated soils (Reynolds and Elrick, 1991). A large α indicates that the unsaturated flow is dominated by gravitational force, i.e., more significant macropore flow.

In October 2004, soil samples were collected near each infiltration site for laboratory analysis of soil texture, bulk density, soil water retention characteristics, and other physical and chemical properties, including pH, CEC, total C, and element composition. All of these analyses followed the standard soil survey procedures. In addition, three vertically oriented soil core samples (0.06 m-high and 0.054 m-diameter) were collected in May 2006 to determine the saturated hydraulic conductivity (Ksat) in the laboratory using the constant head method (Klute, 1986).

It should be noted that the soil samples were collected from a relative small area, and the infiltration experiments in this study were conducted at a small scale (within about 1 m^2 area). Spatial variation generally exists within a soil series; consequently, the measured soil texture and hydraulic properties may not completely represent the mean properties of the corresponding soil series and land use. Nevertheless, we did carefully select each site to be the "representative" of the treatment being considered.

2.3. Statistical analysis

All statistical analyses were conducted using the SAS (SAS Institute Inc., Cary, NC). All infiltration rates were log-transformed before performing the statistical analyses. The HOVTEST option (Levene's test) in the MEANS statement was used to test the homogeneity of variance. The result showed that the assumption of homogeneity of variance stands in our

Table 2
Analysis of variance of surface soil hydraulic conductivity ($\log_{10} K$, in $\times 10^{-6}$ m/s) measured at various water potentials (−0.12, −0.06, −0.03, −0.02, −0.01, and 0 m) using tension infiltrometers, showing the effects of soil series, land use, measurement time, and their interactions

	$\psi=-0.12$		$\psi=-0.06$		$\psi=-0.03$		$\psi=-0.02$		$\psi=-0.01$		$\psi=0$	
Effects	MS	p	MS	p	MS	p	MS	p	MS	p	MS	p
Soil series	0.18	0.51	0.05	0.73	0.30	0.17	0.66	<0.01***	0.49	0.04**	0.63	0.02**
Land use	0.15	0.58	0.19	0.18	0.58	0.02**	0.16	0.34	0.32	0.12	0.37	0.12
Time	4.33	<0.01***	3.89	<0.01***	8.71	<0.01***	5.02	<0.01***	4.27	<0.01***	3.10	<0.01***
Soil series*Land use	0.44	0.05*	0.37	<0.01***	0.33	0.06*	0.44	<0.01***	0.39	0.02**	0.36	0.06*
Soil series*Time	0.02	0.96	0.25	0.09*	0.48	0.04**	0.51	0.02**	0.48	0.03**	0.25	0.28
Land use*Time	0.70	0.03**	0.16	0.24	0.58	0.02**	0.51	0.02**	0.39	0.07*	0.17	0.44
Soil series*Land use*Time	0.44	0.05*	0.27	0.01**	0.19	0.35	0.10	0.72	0.19	0.33	0.31	0.12

MS is the mean square of the effect.
Values of p are indicated using three significance levels (*** $p<0.01$, ** $p<0.05$, * $p<0.1$).

dataset. The significance tests of the treatment effects (soil series, land use, and measurement time) and their interactions were performed using the Analysis of Variance (ANOVA) within the General Linear Model (GLM) procedure. Note that during the field infiltration experiments, some tension infiltrometers encountered unexpected physical or electrical problems, and thus those were excluded from the analysis, leading to some treatments having replicates of 3 or 4 instead of 5. For such unbalanced experimental design (i.e., the number of replicates not being the same for all treatments), the Least Squares Means (LSMEAN) statement within the GLM is more suited. The option (ADJUST=TUKEY) of the LSMEAN was used for multiple-mean comparison of the measured soil hydraulic properties (K_ψ's and α for macropores) among treatments. Because of the considerable variability encountered in the field, we chose to use multiple significance levels of 90% ($p<0.1$), 95% ($p<0.05$), and 99% ($p<0.01$) in our analysis.

3. Results and discussion

3.1. Impact of soil physical properties on hydraulic conductivity

Soil hydraulic conductivities were significantly different among the four soil series at potentials of −0.02, −0.01, and 0 m of water (Table 2). This is apparently related to their differences in texture and structure. The Hagerstown and Glenelg soils had significantly lower sand content but higher silt and clay percentages than the Joanna and Morrison soils (Table 1). The bulk density and organic carbon of the surface soils were also different among the four soil series, although not statistically significant because of the variability within each soil series with different land uses (Table 1). The Morrison soil series had significantly lower plant available water (PAW, i.e., the difference of the volumetric water contents between 33 kPa and 1500 kPa) than the Joanna and Glenelg soil series, which was related to its significantly higher sand content.

The soil texture/structure parameter (α) estimated by Eq. (1) is listed in Table 3 for macropores at each study site. As suggested by Luxmore (1981), Smettem and Ross (1992), and Baird (1997), the potential of −0.03 m was used here as the highest potential for macropores to effectively transmit water. The estimated $\alpha_{\psi>-0.03\ \mathrm{m}}$ values of the Hagerstown soil were significantly higher than those of the other soil series (Table 3), indicating that the gravitational force contributed more to the macropore flow in the Hagerstown surface soil than in the other three soils. While we were aware that not all fine-structured soils have well-developed structures (e.g., the Glenelg series in this study), the Hagerstown series did show larger $\alpha_{\psi>-0.03\ \mathrm{m}}$ values than the coarse-textured soils (such as the Morrison and Joanna) because of the well-developed structure in the Hagerstown, suggesting a greater tendency for macropore flow to occur in the Hagerstown. This is consistent with the findings of Lin et al. (1997). The Hagerstown soil had the lowest sand content and bulk density but highest clay and silt contents among the four soil series studied, which lead to the overall highest $\alpha_{\psi>-0.03\ \mathrm{m}}$ values.

3.2. Impact of land use on soil hydraulic conductivity

The land use effect on surface soil hydraulic conductivity was significant only at water supply potentials of −0.03 m based on our field infiltration measurements (Table 2). However, the interactions between the land use and measurement time and between the land use and soil series were statistically significant at other potentials (Table 2). As a result, the land use effect may have been masked by the interaction with other factors. We performed the statistical analysis for the infiltration experiments conducted in May and October separately, and the results showed that land use had greater impacts in October than in May, while soil series had greater impacts in May than in October (Table 4).

Table 3
Soil texture/structure parameter, α (m^{-1}), for macropores ($\psi>-0.03$ m) in each of the combinations of four soil series and four land uses

Soil series–land use	Woodland	Cropland	Pasture	Urban	Average
Glenelg	62 (30)	65 (28)	69 (17)	47 (22)	61 (26) a
Hangerstown	73 (24)	88 (30)	79 (41)	85 (24)	81 (30) b
Joanna	83 (34)	73 (47)	59 (19)	60 (21)	69 (33) a
Morrison	79 (38)	73 (43)	66 (26)	59 (20)	69 (38) a
Average	74 (32) A	75 (37) A	69 (28) A	63 (25) A	

The number in the parenthesis is one standard deviation of the mean. Capital letters after the parenthesis indicate the significance test of mean difference among the four land uses at $p<0.1$, while lower letters indicate the significance test of mean difference among the four soil series at $p<0.1$.

Table 4
Analysis of variance of surface soil hydraulic conductivity ($\log_{10} K$, in $\times 10^{-6}$ m/s) measured at various water potentials (−0.12, −0.06, −0.03, −0.02, −0.01, and 0 m) using tension infiltrometers for May (2004 and 2006) and October (2004 and 2005), respectively, showing the effects of soil series, land use, and their interactions in two measurement time

Season	Effect	$\psi=-0.12$		$\psi=-0.06$		$\psi=-0.03$		$\psi=-0.02$		$\psi=-0.01$		$\psi=0$	
		MS	p	MS	p	MS	p	MS	p	MS	p	MS	p
May	Soil series	0.80	0.50	1.83	0.15	3.69	0.02**	5.97	<0.01 **	4.65	<0.01***	2.83	0.04**
	Land use	0.87	0.46	1.89	0.14	1.23	0.31	0.72	0.54	1.21	0.31	1.09	0.36
	Soil series*Land use	1.08	0.38	2.37	0.02**	0.99	0.45	1.06	0.40	1.56	0.14	1.82	0.07*
October	Soil series	0.22	0.88	0.95	0.42	1.53	0.21	2.43	0.07*	1.53	0.21	0.46	0.71
	Land use	2.33	0.08*	1.17	0.323	4.88	<0.01***	4.39	<0.01***	3.07	0.03**	2.94	0.04**
	Soil series*Land use	2.33	0.02**	3.09	<0.01***	1.84	0.07*	3.00	<0.01***	1.96	0.05*	1.56	0.14

MS is the mean square of the effect. Values of p are indicated using three significance levels (*** $p<0.01$, ** $p<0.05$, * $p<0.1$).

Woodland generally had a much higher total carbon content and a lower bulk density (Table 1), as well as limited human-induced changes, than other land uses studied. Thus woodland soils generally showed higher $K(\psi)$ values (Table 5 and Fig. 1). Soil total carbon content showed a general increasing trend from urban to cropland, pasture, and woodland (1.1±0.4, 1.3±0.3, 2.2±0.6, and 10.3±2.2%, respectively). The higher total carbon content in the woodland soils likely has led to a higher soil aggregate stability and a greater number of macropores. In addition, the impacts from rain drops on the surface soil hydraulic conductivity are likely reduced for woodland because of its more consistent ground cover all year round. However, the woodland's higher $\alpha_{\psi>-0.03\ \mathrm{m}}$ values (than the other three land uses) were only well expressed in the coarse-textured soil series (Morrison and Joanna) (Table 3).

Land use and management practice, such as tillage, grazing and gardening, all influence macropores and the continuity of the macropore network. The surface compaction effects of pasture and cropland tend to result in higher bulk density and lower hydraulic conductivity under those land uses as compared to the woodland (Fig. 1). Urban soils generally experience even more compaction during construction, giving rise to a generally higher bulk density and lower hydraulic conductivity (Table 1). However, the Glenelg soil was the only series under this study that had urban site displaying the lowest hydraulic conductivity among the four land uses studied (Fig. 1). The Glenelg urban soil had a poor structure, while the other three soils' urban sites had developed better structure in the surface soils because of the well-maintained lawn. Age of the urban development is another factor that modifies the effect of urbanization on soil properties.

Table 5
Surface soil hydraulic conductivity (K, in $\times 10^{-6}$ m/s) at water potential (ψ) of −0.03 and 0 m in each of the soil series–land use combinations, separated by measurement time (May vs. October)

	Soil series–land use	Woodland	Cropland	Pasture	Urban	Average
Ψ=0 m						
May	Glenelg	17.1 (16.6)	23.1 (16.5)	18.8 (15.7)	8.2 (5.8)	16.8 (14.9) a
	Hagerstown	18.0 (9.5)	31.2 (17.9)	23.9 (21.1)	45.8 (36.1)	29.7 (23.0) b
	Joanna	38.1 (22.5)	10.8 (11.9)	20.6 (15.5)	22.6 (15.8)	23.0 (18.0) ab
	Morrison	30.6 (16.7)	15.2 (13.9)	18.4 (9.1)	16.1 (8.3)	20.1 (13.1) ab
	Average	26.0 (17.8)A	20.1 (16.4)A	20.4 (16.4)A	23.2 (22.2)A	
October	Glenelg	20.2 (24.7)	9.7 (10.1)	13.6 (8.4)	5.1 (5.4)	12.1 (18.1) a
	Hagerstown	16.2 (9.8)	10.7 (9.7)	6.4 (4.9)	13.8 (16.8)	11.8 (15.1) a
	Joanna	26.6 (17.4)	14.7 (4.7)	3.1 (1.8)	20.4 (13.3)	16.2 (13.3) a
	Morrison	19.9 (16.6)	10.4 (13.5)	17.7 (30.7)	22.0 (11.6)	17.5 (18.4) a
	Average	20.7 (17.1)B	11.3 (9.4)AB	10.2 (9.6)A	15.3 (13.8)AB	
Ψ=−0.03 m						
May	Glenelg	1.6 (2.1)	1.6 (1.4)	2.6 (2.3)	1.0 (0.6)	1.7 (1.8) a
	Hagerstown	1.6 (0.3)	1.8 (0.9)	2.1 (0.9)	3.4 (1.2)	2.2 (1.1) b
	Joanna	3.0 (3.5)	2.2 (2.5)	3.8 (2.8)	2.7 (1.3)	3.8 (5.4) b
	Morrison	1.9 (0.6)	1.6 (1.0)	1.7 (0.9)	3.4 (2.0)	2.2 (1.4) ab
	Average	2.0 (1.8) A	1.8 (0.7) A	2.5 (0.6) A	2.6 (1.3) A	
October	Glenelg	1.3 (0.5)	1.2 (0.5)	0.9 (0.6)	0.6 (0.2)	1.0 (0.9) a
	Hagerstown	1.0 (0.7)	0.5 (0.3)	0.8 (0.9)	0.4 (0.3)	0.7 (0.7) a
	Joanna	1.5 (0.8)	1.2 (1.0)	0.4 (0.3)	3.0 (1.7)	1.5 (1.9) a
	Morrison	1.0 (0.5)	0.8 (0.4)	0.7 (0.6)	2.4 (1.9)	1.3 (1.3) a
	Average	1.2 (0.6) B	0.9 (0.7) AB	0.7 (0.7) A	1.6 (1.7) B	

The number in the parenthesis is one standard deviation of the mean. Capital letters after the averages indicate the significance test of mean difference among the four land uses at $p<0.1$, while lower letters indicate the significance test of mean difference among the four soil series at $p<0.1$.

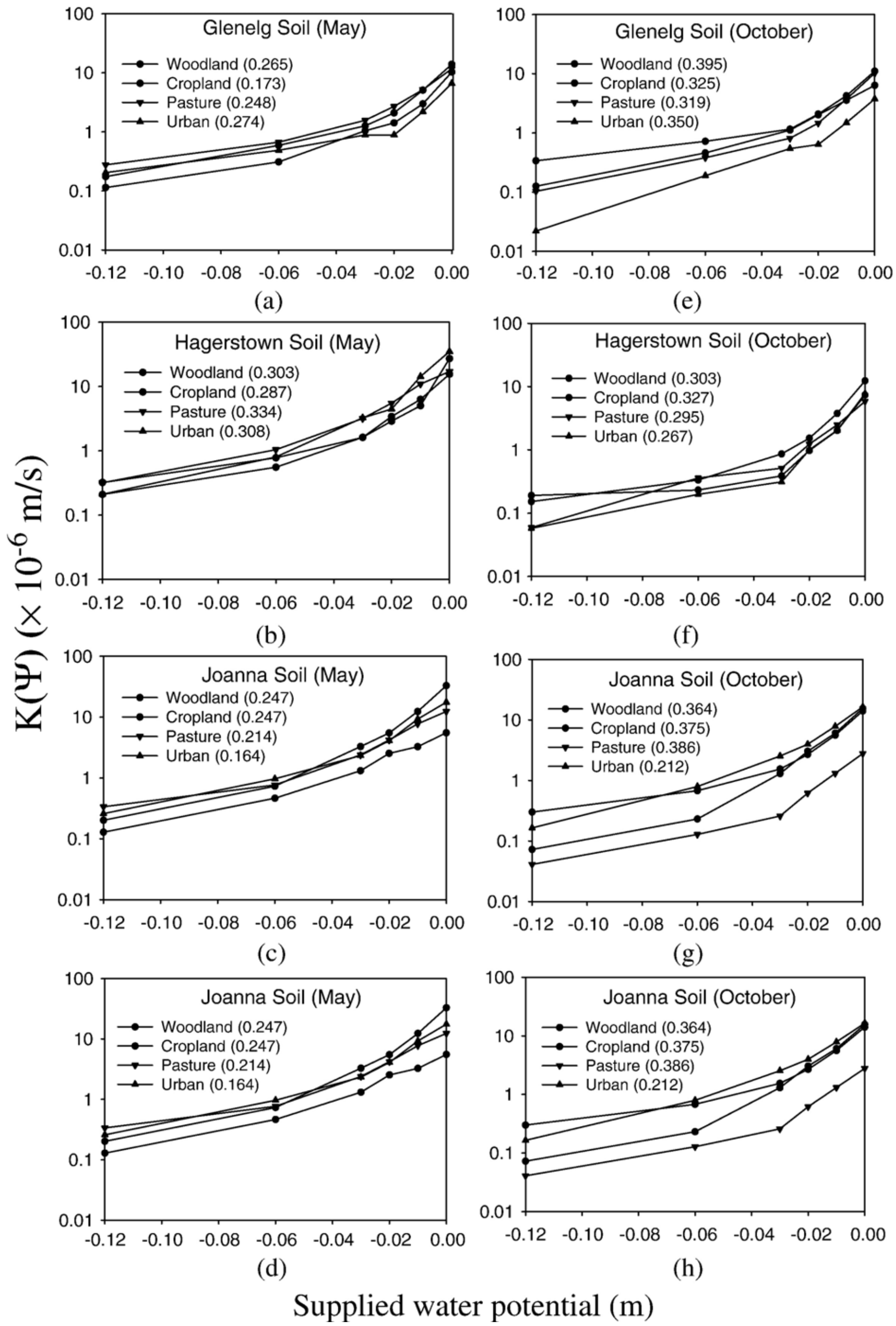

Fig. 1. Soil hydraulic conductivity as a function of water supply potential among the four land uses within each of the four soil series measured in May (a–d) and October (e–h), respectively. Geometric means are plotted in log scale for each potential measured with tension infiltrometers. The number in parenthesis is the averaged initial volumetric soil moisture content at each site in May or October.

The Glenelg urban site was continually worked on throughout the 2004 as a drainage ditch was being installed, whereas the other three sites were more established (over 5 years) with grass growing well that have helped improve the surface soil structure.

The five replicated tension infiltrometer measurements within the small area still displayed a large spatial variation, leading to a less significant difference in mean soil hydraulic conductivity among the four land uses in statistical tests. Particularly at field-saturated or near-saturated conditions, non-uniformity and macropore flow may have caused more heterogeneity in measurements, resulting in some difficulties in reproducing results (McKenzie et al., 2001). Short distance spatial variability in soil hydraulic properties has also been commonly reported at a comparable measurement scale (e.g., Lin et al., 1996).

3.3. Temporal change of soil hydraulic conductivity

The analysis of variance (Table 2) indicated that the measurement time had the greatest impact on all measured hydraulic conductivities ($p<0.001$) in the soils studied, whereas

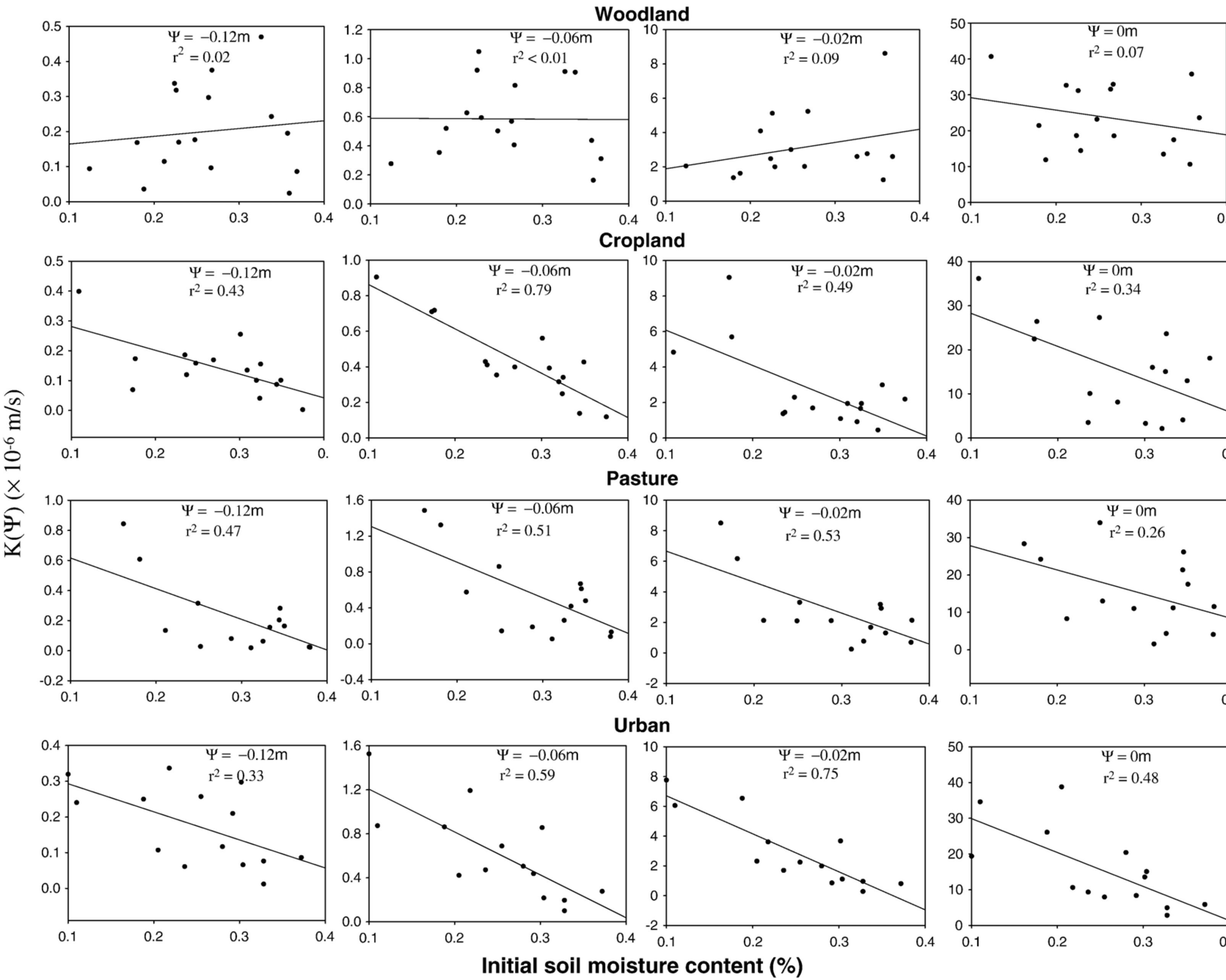

Fig. 2. Correlation between soil hydraulic conductivity and initial volumetric soil moisture content at various water supply potentials (ψ=−0.12, −0.06, −0.02, and 0 m) for each land use. Negative relationships are observed for the cropland, pasture, and urban land uses, while no correlation is found for the woodland.

the impacts by the land use were limited to $K_{\psi=-0.03}$ ($p<0.05$) and the impacts by the soil series were statistically significant only for $K_{\psi=-0.02}$ to $K_{\psi=0}$ ($p<0.05$). This indicated that the temporal variation of surface soil hydraulic conductivities was greater than the spatial variation associated with the differences in soil series and land uses. The interaction between the measurement time and land use was statistically significant while the interaction between the measurement time and soil series was not (Table 2). Significant time effect and its interactions with spatial factors (topography) have also been observed in other studies (e.g., Heddadj and Gascuel-Odoux, 1999). We acknowledge that we only conducted two infiltration tests in each of May and October, which may not completely represent the dynamic soil hydraulic properties in these two months.

We also found that surface soil hydraulic conductivities were higher in May (at lower initial soil moisture) than in October (at higher initial soil moisture) at most of the study sites (Table 5 and Fig. 1). The field-saturated hydraulic conductivity for the cropland site of the Glenelg soil, for example, was $23.1\pm 16.5\times 10^{-6}$ m s^{-1} in May, but $9.7\pm 10.1\times 10^{-6}$ m s^{-1} in October. The overall averaged initial soil moisture content at all of the 16 sites was 0.25 ± 0.07 m^3 m^{-3} in May, and 0.31 ± 0.07 m^3 m^{-3} in October during the study period. Our results showed that soil hydraulic conductivity had a negative relationship with the initial soil moisture content at the surface under each of the supply water potentials (only $\psi=-0.12$, -0.06, -0.02, and 0 m are shown in Fig. 2) for the cropland, pasture, and urban land uses, while no such relationship was observed for the woodland (Fig. 2). This suggested that the hydraulic conductivity of the woodland soils was less sensitive to the soil moisture change over time and hence was more temporally stable.

The increase of soil hydraulic conductivity under drier condition was attributed to the increase of soil macroporosity and the enhanced expression of pedality (Lin et al., 1998). Soils in May were often associated with more animal burrows such as earthworm channels, and more appearance of desiccation cracks at the surface, all of which were observed *in situ* during our field measurements.

4. Conclusions

While limitations existed in this study because of the small infiltration area used at each site of soil series–land use combination and the limited number of repeated measurements over time, useful information have been gained from this study. Our results showed that surface soil hydraulic properties (including field-saturated and near-saturated hydraulic conductivities and a soil texture/structure parameter α) were impacted by the differences in land uses and soil types. But temporal variation of surface soil hydraulic properties appeared to be greater than their spatial variation caused by land use and soil series. Consequently, the impacts of land use and soil series on the measured soil hydraulic properties varied significantly with the measurement time. Soils measured in this study generally had a lower moisture content in May than in October, resulting in generally higher hydraulic conductivities in May than in October. The impacts of land use on the soil hydraulic properties were more obvious in October than in May, while the soil series had the greater impacts in May than in October. The temporal change of soil hydraulic properties was less obvious for woodland compared to other three land uses, because of less human-induced impacts and more consistent ground cover year-round. Woodland showed significantly higher hydraulic conductivity than other three land uses in October, but not in May. This was due to the increased hydraulic conductivity for other three land uses in May that were associated with the drier soil moisture condition and related management practices in spring that gave rise to more significant macropore flow. This suggests that for a given soil genoform (original soil series), the difference of soil hydraulic properties among phenoforms (different land uses) is a function of time. Under certain conditions, phenoforms may show similar hydraulic properties while under other conditions they may show significantly different properties. The initial soil moisture content was found to be an important variable responsible for the temporal variation of surface soil hydraulic conductivities.

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